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Urban-scale building energy consumption database: a case study for Wuhan, China

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Abstract

Building energy consumption accounts for 30% of the overall energy end use worldwide. This number is even much higher in urban areas. With rapid urbanization in China, cities are expanding with new constructions. It is essential to create an updated urban-scale building energy consumption database to represent energy use for different types of buildings in China, which could help urban planners, managers and decision makers to understand temporal and spatial building energy consumption distribution and ensure required electricity and/or gas supply. However, such urban-scale database is rarely found in China. This paper creates baseline EnergyPlus models for residential, small office and large office buildings and validates the baseline models using survey data from literature. Parametric simulations are conducted to consider different design factors, such as building enclosure, lighting power density, equipment power density, HVAC schedule, etc. In total 351 EnergyPlus models are generated to cover different energy use intensity scenarios. Data-driven regression analysis is conducted to predict building energy consumption using building price/rent. The prediction results are expected to provide design decision support for urban planning and power distribution for new constructions.

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Keywords: Urban-scale; Building energy simulation; EnergyPlus; Regression; Building price/rent

1. Background and Introduction

Buildings consume more than one-third of the final energy consumption worldwide [1]. This number is even higher in developed countries. For example, according to the U.S. Energy Information Administration (EIA) in 2014,

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residential and commercial buildings accounted for 40% of total energy in the United States [2]. Urbanization is one of the critical theme and challenges in the past and this century, with tremendous increase in energy consumption. The United Nations predicted that, by 2050, 66% of the world's population will live in urban areas [3]. Especially with rapid urbanization in China, cities are expanding with new constructions every year. It is essential to create an updated urban-scale building energy consumption database to represent energy use for various applications including energy benchmarking, urban planning, citywide energy supply-demand strategy development, etc. While promising, due to the complexity in developing the simulation models and the intense computational requirement, the urban scale building energy simulation studies have only started in the past a few years.

No matter how large the city scale is, the basis is still individual building energy simulation. Currently, the common methods for building energy simulation is physics based approach and data driven approach. The first approach uses the general physics theories and relationships between energy consumption and temperature, solar radiation, internal load, etc. The other approach purely captures the under knees relationship between energy consumption data, weather data and system operation data. Either of these two approaches have its own pros and cons, in terms of accuracy, robustness, and computational efficiency.

As we will need to create an urban scale building energy database, the data driven approach will not be a good choice as it is highly dependent on the operation data, which does not exist. Additionally, collecting the detailed energy consumption and operation data for the whole city is very hard in most of the circumstances. Therefore, most of the existing studies uses the physics based approach.

The general process of physics based approach is as follows. We firstly collect the information about building geometry, which usually can be obtained from city planning or GIS database, construction and energy system operation, which can be obtained from the "energy saving standard", as well as the weather information, which is easily accessible from weather stations. We then generate the simulation models using the off-shelf tools. In this step, simulation model generalization and simplification are needed. The next step is execution the simulation models and analysis simulation results. After the baseline scenarios are simulated and validated, we then can simulate and predict the future energy consumption to assist urban planning and for other specific purpose.

Several urban energy simulation tools have been developed using the similar physics approach described above, such as the CityBES [4], building energy simulation model (UBEM) [5] and Urban-EPC [6], etc. However, the case studies are for large cities in the US, where rapid urbanization has almost been completed. The city boundary and building energy consumptions are quite stable without many new constructions. This is not true for large cities in China, where buildings with different year of built exist in the same space. Spatial and temporal features are more important. It allows planners and policy makers to foresee the urbanization through the lens of energy performance. This paper generates an urban-scale energy consumption database for residential and commercial buildings in Wuhan as a case study. The database can be further used to develop the urban energy consumption platform.

2. Baseline EnergyPlus Model description

1.1. Residential building

To generate a generic building model for the city-scale energy database, baseline EnergyPlus model is created. Figure 1a shows the geometry of a typical residential building. The building has 10 floors with a total building area of 7,836 m2. Each floor has eight apartments and one corridor. The area of each apartment is 88m2.

Local building design standard is used to define design parameters for building enclosure, HVAC system and building loads, etc [7]. Details of baseline model setting can be found in Appendix Table 1. Ductless mini-split room heat pump is assumed to provide cooling and heating. To create a semi-closed loop for building energy simulation, model calibration is conducted. This paper considers occupants' actual energy use behavior. The heating and cooling schedules are set to the average heating and cooling times (days/year and hours/day) in hot summer and cold winter zone from CRECS survey data. Wuhan's hourly weather data is used to simulate annual energy performance [8].

The annual building energy performance is simulated using EnergyPlus software and validated using the CRECS survey data. The CRECS2012 survey was conducted by Renming University in 2012 to collect data from 1450 residential buildings across 26 provinces in China. The CRECS2012 data includes six parts: household characteristic, housing unit characteristics, kitchen and home appliances, space heating and cooling, residential transportation, fuels used and bills and perception and attitude [9].

Consider the climate condition in Wuhan, 218 valid instances from the urban areas in hot summer and cold winter climate zone is used to calibrate the baseline residential model. To generate a generic building model for the city-scale energy database, baseline EnergyPlus model is created. Figure 1b shows the annual energy consumption of the baseline residential building. It can be observed that due to heating and cooling energy consumptions only account for about 30% of the total electricity consumption. People tends to only use the heat pumps for limited time to save electricity bills, which creates important behavioral opportunities for energy savings. The simulated result total building electricity consumption is 27.8kWh/m2, which matches well with the average electricity consumption from the China Residential Energy Consumption Survey (CRECS) survey (25.8kWh/m2). The low energy usage due to occupants' behavior leads to a lower electricity consumption compared with that (35.3kWh/m2) in the Guideline for Energy Consumption Quota of Civil Buildings in Wuhan [10].

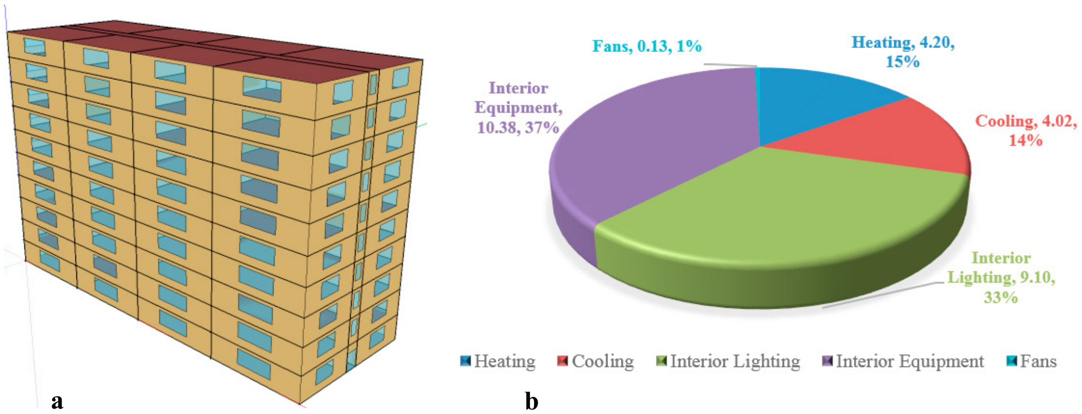

Figure 1 a: Geometry of the residential building model; b: Baseline residential building simulated energy consumption breakdown [kWh/m2]

1.2. Commercial building

Depending on different total building areas and HVAC systems, the office building is further divided into small office (<20,000m2) and large office building (≥20,000m2). Each floor has four external zones and one core zone. Figure 2 shows the geometry of typical commercial buildings. The small office building has 11 floors and the large office building has 18 floors. Similar to residential building, small office building uses ductless mini-split room heat pump with same heating and cooling schedules. While the HVAC systems for large office building are chiller and cooling tower for cooling and boiler for heating. Public building design standard is used to define design parameters for building enclosure, HVAC system and building loads, etc [11]. The detailed settings for baseline models are summarized in the Appendix (see Table 1). Figure 3 indicates the building energy consumptions of the baseline models.

3. Parametric simulations

After the baseline model is validated, parametric simulations are conducted to generate a numerical data base for Wuhan's building energy consumption. Eight different design parameters are considered to cover different Building enclosures, Infiltration rate, Heating and cooling schedules, Lighting power density and Equipment power density. To differentiate buildings' year of built, three levels (high, medium and low) of building enclosures are studied by coupling U factors of different parts (external wall, slab, roof and glass).

According to statistical analysis of the occupancy energy usage behavior from CRECS data, thirteen heating and cooling schedules are covered, ranging from 5% to 95% of the survey data, to reflect different occupants' behaviors. For example, 5% means the top 5% of the most efficient energy usage in terms of heating and cooling hours per day and days per year. Because people with higher demand on heating and cooling usually use more energy, it is assumed that the lighting and plug/equipment loads are coupled with air conditioning schedules. So the total number of parametric models of each building type is 117. Figure 4 shows an example of the small office building scenario. The combination of small office building baseline model is highlighted in yellow.

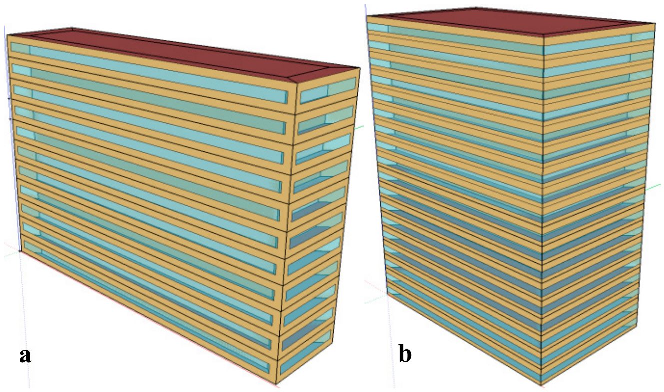

Figure 2 Baseline commercial building geometries (a: small office, b: large office)

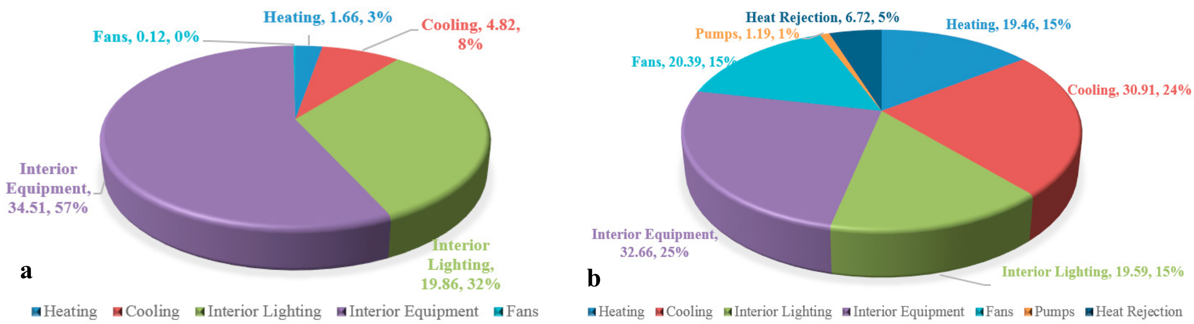

Figure 3 Baseline commercial buildings simulated energy consumption breakdown [kWh/m2] (a: small office, b: large office)

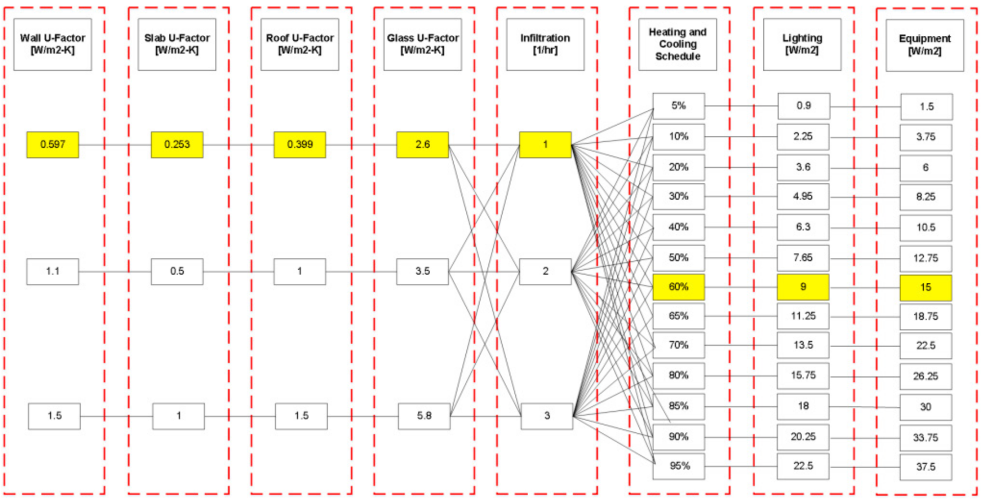

Figure 4 117 parametric combinations of the small office building model

4. Results and discussion

The building energy performance of the parametric combinations defined in Section 4 are simulated using EnergyPlus. In total 351 (117 residential + 117 small office + 117 large office) EnergyPlus models are generated to cover different energy use intensity scenarios. Taking residential building as an example, Figure 5 shows the stochastic simulation results of the annual energy consumption, which gives the decision maker an electricity consumption range for each building type. It is noted that the energy consumptions are based on pure stochastic simulations defined in Section 4, assuming a uniform distribution of the 117 parametric design scenarios of each building type without any weighting factor for each scenario. In reality, there may be less people in the very low (left) and very high (right) energy consumption sections. To get a more realistic energy consumption distribution, we collected Wuhan's housing price (for residential building) and rent (for office building) distribution, and adjusted the energy distribution accordingly. Furthermore, to provide more practical high-level suggestions for urban planners and energy policy maker, a data-driven regression model is conducted to predict building energy consumption using building's price/rent. To support third-party application, the core simulation APIs are wrapped using RESTful WebService. Figure 6 shows the main interface for output testing and demonstration.

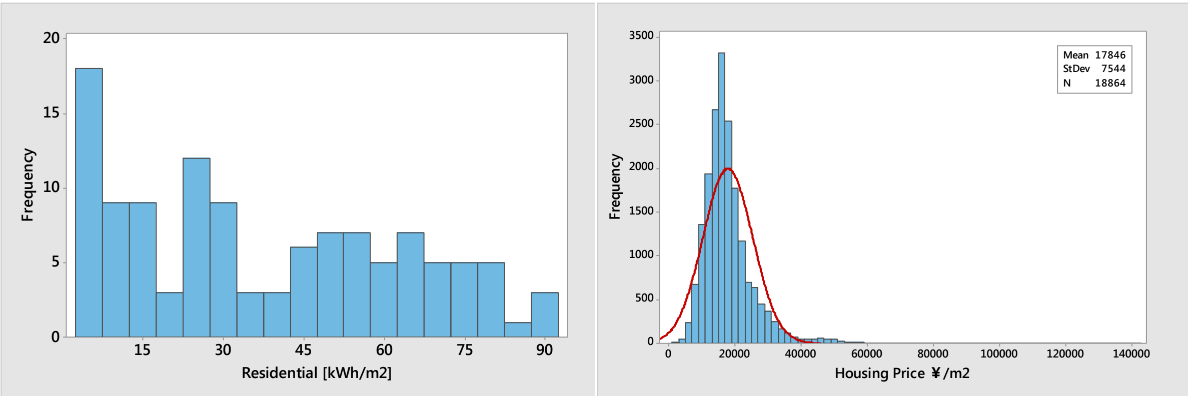

Figure 5 Left: Annual residential building energy consumption distribution of the parametric scenarios; Right: Wuhan housing price

Figure 6 Output of a RESTful WebService

5. Conclusions

Urban scale building energy simulation can play an essential role in urbanization. It allows planners and policy makers to foresee the urbanization through the lens of energy performance. It is also the right time to start this research and study in China, as the basic tools are already developed and ready to use, and the requirement for citywide energy consumption information is urgent for city planning and energy strategy making.

To develop such urban-scale building energy platform, this paper demonstrates the process of generating a building energy consumption database for residential and commercial buildings from stochastic simulations. The baseline EnergyPlus model is validated using energy usage input from survey data. Energy consumption density of three different construction levels are considered to reflect buildings constructed in different years. Energy consumption distributions are adjusted using Wuhan's housing price and rent data. This database is further used to predict building energy consumption through regression analysis. In the next step, a user interface is developed to provide energy prediction and decision support.

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Appendix

Table 1 Baseline EneryPlus model settings

Input parameters	Unit	Office building	Residential Building
External wall insulation	W/m²K	0.597	0.88
Roof insulation	W/m²K	0.399	0.447
Ground floor insulation	W/m²K	0.253	1.2
External Windows	W/m²K	2.6	2.7
Infiltration rate	ACH	1	1
Lighting power dentistry	W/m2	9	Apt: 4.2, Corridor: 1.8
Equipment power density	W/m2	15 W/m2	Plug load: 2, Kitchen: 5
Occupancy density	m2/person	10	2
HVAC system	-	Mini-split air conditioner (small office) Chiller + Natural gas boiler (large office)	Mini-split air conditioner
Heating/Cooling setpoints	°C	20.5 / 23.5	18 / 26
Heating Schedule	-	9:00-12:00, 1/1-2/14 (small office) 8:00-15:00, 1/1-2/14 (large office)	19:00-22:00, 1/1-2/14
Cooling Schedule	-	12:00-16:00, 7/18-8/31 (small office) 10:00-17:00, 7/18-8/31 (large office)	18:00-22:00, 7/18-8/31

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